Dense, low-power sensor network for three-dimensional thermal characterization of large-scale atria spaces

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

Citation: Gong, Nan-Wei, Laura Ware, Steve Ray, Gary Ware, Brett Leida, Tim Ren, Phil London, et al. “Dense, low-power sensor network for three-dimensional thermal characterization of large-scale atria spaces.” In 2012 IEEE Sensors, 1-4. Institute of Electrical and Electronics Engineers, 2012.

As Published: http://dx.doi.org/10.1109/ICSENS.2012.6411177

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Version: Author's final manuscript

Accessed: Fri Feb 01 14:43:37 EST 2019

Citable Link: http://hdl.handle.net/1721.1/80767

Terms of Use: Creative Commons Attribution-Noncommercial-Share Alike 3.0

Detailed Terms: http://creativecommons.org/licenses/by-nc-sa/3.0/
Dense, Low-Power Sensor Network for Three-Dimensional Thermal Characterization of Large-Scale Atria Spaces

Nan-Wei Gong1, Laura Ware1, Steve Ray2, Gary Ware2, Brett Leida2, Tim Ren2, Phil London2, Ashley Turza1, David Way1, Leon Glicksman3, Joseph A. Paradiso1
1Responsive Environments Group, MIT Media Lab, Cambridge, MA 02139, USA
2Schneider Electric, North Billerica, MA 01862, USA
3Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract—We describe the design and implementation of a dense, low-power wireless sensor network for fine-grained three-dimensional thermal characterization of a large open indoor space. To better understand the airflow dynamics and ensuing energy efficiency potential of this type of modern architectural design, we developed a sustainable wireless mesh network consisting of 50 sensors hung on an array of thin cables in a 210 m2, 14.2 m tall atrium for real-time temperature and humidity monitoring. The goal is to create compact wireless measurement sensor blocks for dense coverage in the building. We demonstrate the implementation through a preliminary analysis, which includes the evaluation of temperature distribution discrepancies with computer-simulated results and data taken during natural ventilation to illustrate the nontrivial, well-mixed temperatures observed during the studies.

I. INTRODUCTION

The energy usage for heating, cooling and ventilation in a commercial building has a major impact on commercial energy consumption. However, most research on thermal characterization for energy efficiency focuses on monitoring energy use and system design of data centers, where the geometry of the space is simple and symmetric, and the heat sources (power lines and servers) are well confined. Although atria have already become a common feature of new building designs, the complex flows and heat transfer in atrium environments, such as turbulent natural convection or conjugate heat transfer from solar radiation, are not usually included as factors in energy simulation programs. Real-time data measurement for the validation of computational fluid dynamics simulations is critical to establish energy-efficient control matrices for building management systems [1]. However, full scale measurements [2] are rarely performed for customized building energy profiling. Our motivation is to create an easy-to-deploy wireless sensor system for real-time energy profiling and control feedback for building management systems. The work was inspired by the mobile measurement technology (MMT) from IBM Research [3-4], a measurement cart for rapid data gathering and customized modeling used to monitor and discover energy-saving opportunities. Such systems are targeted for highly symmetric, cloistered spaces. However, for our purpose of evaluating and studying large-scale atria spaces, we need a wireless system that can be freely distributed throughout large open areas to gather three dimensional temperature and humidity data for finding energy saving opportunities and perform full-scale experiments, such as determining air flow and heat transfer distributions in atrium environments.

We have deployed a wireless environmental sensor network for three-dimensional thermal characterization of atria geometries. Each sensor unit is a standalone node capable of communicating with the others through a wireless mesh network and is set up as an end device. The data collected are forwarded from Zigbee router devices that are deployed around the outlets on surrounding walls.

Figure 1. Left: image of 65 wireless temperature/humidity sensors suspended with wires in 5 rows and three layers mapped to the corresponding floors in an atrium space.

The work was sponsored by Schneider Electric and the MIT Media Lab
Figure 1 shows the sensor with its perforated enclosure and the atrium space where we deployed our experiment. Each sensor was hung in midair on a 49-strand stainless steel cable. The sensors are 2.84 meters apart from each other in our setup.

II. METHOD AND EXPERIMENT

Our work began with the development of a low-power wireless sensor system. Each sensor node consists of a temperature sensor (LM35CZ) and a humidity sensor (HIH-4030) with individual microprocessor (ATMEGA 164), which controls the wireless data transmission and power management. Table 1 is the list of components in the hardware design. We calculated the power consumption of each component and operating modes assuming one sample every 3 minutes estimated that each node could run for 96.75 days with two 1.5V 2500mAh batteries. The performance could be drastically improved if the sampling rate was lower or a more efficient microprocessor and a properly duty-cycled temperature/humidity sensor was employed [5].

<table>
<thead>
<tr>
<th>Component</th>
<th>uA</th>
<th>Duty Cycle</th>
<th>uA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM35CA</td>
<td>91</td>
<td>1</td>
<td>91</td>
</tr>
<tr>
<td>HIH-4030</td>
<td>200</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>LDO</td>
<td>40</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>MCU (active)</td>
<td>2100</td>
<td>0.0021</td>
<td>4</td>
</tr>
<tr>
<td>MCU (Idle)</td>
<td>500</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>Xbee - xmit</td>
<td>215000</td>
<td>0.0007</td>
<td>155</td>
</tr>
<tr>
<td>Xbee - receive</td>
<td>55000</td>
<td>0.0013</td>
<td>76</td>
</tr>
<tr>
<td>Xbee - idle</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td>1077</td>
</tr>
<tr>
<td>Battery Life</td>
<td></td>
<td></td>
<td>96.75</td>
</tr>
</tbody>
</table>

We performed two studies with this system. The first was a natural ventilation test to evaluate the temperature distribution seen during steady-state and thermal ramp-up from a temperature shock created by turning on a large array of light bulbs placed on the atrium floor. The second study was aimed at comparing simulation results to the temperature distribution obtained using a simple 2-dimensional heat transfer model that interpolated the actual acquired temperature data.

A. Natural Ventilation Test

This system has been used to monitor a naturally ventilated atrium and observe the temperature distribution within the atrium under transient and steady state conditions. To control airflow through the four-story, 2980 m² atrium, all openings to the atrium were sealed with plastic tarps and fire shutters except two openings on the first and third floor. Some of these sealed openings are shown in Figure 2. The third floor opening leads to an auxiliary atrium that is open to the outdoors on the sixth (top) floor. All measurements were taken after 9 pm to eliminate the impact of solar gains on the atrium. A 6 kW array of 100 W incandescent light bulbs was used as a heat source in the middle of the atrium floor to create a temperature difference between the indoor and outdoor air. This temperature difference was intended to induce a buoyancy-driven flow to draw in air through the first floor and exhaust it through the third floor. However, strong winds on the sixth floor and conditioned air from an adjoining building that entered the auxiliary atrium drove the air downward through the third floor opening and out the first floor opening. As a result of this reverse flow, we were able to observe the relative strength of a plume over the 6 kW heat source in a flow dominated by inertial forces.

Our thermal measurement system provided a detailed temperature distribution within the atrium during the transient ramp-up period and after steady state conditions were reached. Surprisingly during both periods, no thermal plume was observed over the heat source. Thirty minutes after the heat source was turned on, no plume was detected in the atrium as shown in Figure 3. The temperature distribution was fairly uniform throughout the four-hour ramp up time. After steady state conditions were reached, the mean temperature was 24.0°C with a standard deviation of 0.68°C, which is slightly larger than the 0.50°C stated accuracy of the temperature sensors. This result was supported by a concurring series of discrete airflow measurements (see below).

In addition to providing insight into plume formation in naturally ventilated atria, this experiment illustrates how the thermal characterization system can shed light on non-trivial flow patterns and building conditions. Furthermore, the low power requirement allows the system to perform long term monitoring that can illuminate seasonal or annual trends within the building. More analysis has been done using this
data, including characterization of a large naturally-ventilated atrium through temperature readings, airflow measurements, detailed airflow visualization techniques, and particle image velocimetry [6].

This assumption is achieved in the MATLAB PDE tool by setting $h$ (convective coefficient, representing $Q$ lost to the environment) equal to 0, along with $Q$ (heat source, representing $Q$ coming from the HVAC). Setting $Q$ and $h$ to 0 causes the system to depend only diffusion due to the boundary temperatures, such that $k$ (conductivity) is no longer important. The equation is only depending on the divergence of the temperature gradient in the 2D space.

Figure 4 is an example of our two-dimensional temperature distribution analysis, where we simulate the heat transfer in vertical slices. To evaluate the thermal effect by airflow in the HVAC system we extracted sensor data for a particular point in time ($\pm$3 min) from all sensors on each floor. We also took sensor readings from the boundaries at the edge of the atrium and used the PDE tool to create 2-D representation of the heat distribution of each floor slice (Figure 4(a)). We then compared the data with a linear interpolation of the real readings from all the sensors. In particular, we noted that the major percentage errors were associated with unmodeled dynamic boundary conditions, such as the supply and return flows on the first floor and wall boundaries at the top of the atrium (Figure 5). The mean error between the actual sensor data and the theoretical model based on steady state heat transfer was $\pm$0.23 degree Celsius. The maximum discrepancy happened on the second floor, where a vent is located, creating a difference of around $+0.9$ degree Celsius.

This approach establishes a quick way to estimate the continuous thermal profile and can provide instant feedback on the adjustment of airflow parameters for building HVAC management.
two simple assumptions—only having measurements at the atrium perimeter under temperature sensors. Slightly larger than the 0.50°C stated accuracy of the sensors was ±24.

Steady state conditions were reached, the mean temperature was fairly uniform throughout the four atria with non-trivial flow patterns and realistic building geometries. Building & Environment 46 (2011) 1343–1353.


The work was sponsored by Schneider Electric, the MIT Media Lab and the MIT Energy Initiative (MITEI). We would like to thank our colleagues from the Responsive Environments Group at the MIT Media Lab.

REFERENCES


